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Lowering the regeneration temperature of a rotary wheel dehumidification system using exergy analysis

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ABSTRACT

Rotary wheel dehumidification is an effective air drying method. This paper analyzes the factors influencing the regeneration temperature from the perspective of exergy. When the dehumidification capacity is fixed, there are two main ways to reduce the regeneration temperature. One is to decrease the exergy destruction during heat and mass transfer in the desiccant wheel, and the other is to decrease the thermal exergy obtained by the processed air after dehumidification. For the first way, the exergy destruction is influenced by the uniformity of the heat and mass transfer driving forces in the desiccant wheel, which can be described by the unmatched coefficient ς. The wheel should be evenly divided, and the two streams of air should have the same flow rate to reduce the exergy destruction. The regeneration temperature can be reduced from above 130 °C to below 70 °C when the air is dehumidified from 20 g/kg to 11 g/kg. For the second way, the thermal exergy obtained by the processed air is influenced by the temperature variation range during dehumidification. Multi-stage dehumidification and pre-cooling are effective mode, with required regeneration temperature lower than 40 °C.

1. Introduction

Effective dehumidification methods are important ways to reduce the energy consumption of air-conditioning systems, especially in humid climates. Rotary wheel dehumidification is an effective air drying method. Such systems are capable of deep dehumidification; there is no moisture surface; and they do not require reheating [1]. After absorbing moisture from the air, the desiccant has to be regenerated by extra heating sources. If the regeneration temperature can be reduced, low-grade heat sources (e.g., solar energy, waste heat from heat pumps, etc.) can replace electrical heating, which will greatly increase system performance.

Rotary wheel systems have been examined extensively in both numerical and experimental studies. Air states, desiccant properties, the ratio of air flow rates (F_r, the ratio of the air flow rate of the processed air to that of the regeneration air), rotation speed, the area ratio (A_r, the ratio of the facial area of the dehumidification side to that of the regeneration side), and wheel thickness have all been investigated in terms of their influence on performance [2–5]. Angrisani concluded that the regeneration temperature has significant influence on the wheel's performance, and that the air flow rates of the regeneration air and the processed air should be identical ($F_r = 1$) in order to maximize performance [2]. In practical applications, $A_r = 3$ is generally used at high regeneration temperatures, while $A_r = 1$ is used for low regeneration temperatures [3]. Chung examined the optimal facial area ratio (A_r) between dehumidification and regeneration as a function of regeneration temperature [3,4]; the results showed that the lower the regeneration temperature was, the lower the optimal A_r was. Two-stage desiccant wheel dehumidification is another effective way to reduce the regeneration temperature [6–10]. Why do F_r, A_r, and the number of dehumidification stages have such significant influences on the regeneration temperature? To explain this finding, the basic factors influencing regeneration temperature must be revealed.

By calculating the exergy change of the two streams of air [11–13] or the exergy change of air and adsorbed water [14] during the dehumidification and regeneration of the desiccant wheel process, exergy destruction can be obtained. Under the same regeneration temperature, the higher humidity removal rate is obtained when the exergy destruction ratio of the desiccant wheel is lower [11]. Thus, the regeneration temperature is influenced by the exergy destruction of the wheel at the same humidity ratio removal rate. Therefore, it is vital to identify ways to reduce exergy destruction.

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Nomenclature

A	facial area, m^2
A_r	facial area ratio of dehumidification side to regeneration side, dimensionless
c_{pm}	specific heat capacity of humid air, J/kg
ex	exergy per mass flow of dry air, kJ/kg
Ex	exergy flow rate, kW
ΔEx	exergy destruction, kW
F	heat and mass transfer area, m^2
F_r	air flow rate ratio of the processed air to the regeneration air, dimensionless
G	air volume flow rate, m^3/h
h	heat transfer coefficient, W/(m^2 °C)
h_m	mass transfer coefficient, kg/(m^2 s)
k	grid number at the angle direction
L	wheel thickness
Le	Lewis number, dimensionless
M	mass removal capacity, kg/s
$\dot{m}$	mass flow rate of the air, kg/s
n	grid number along the thickness direction
NTU	number of transfer units, dimensionless
Q	cooling/heating capacity, W
R_a	gas constant for air, kJ/(mol K)
r	heat of vaporization, J/kg
S_l	slope of saturated air line
T	temperature, K
t	temperature, °C
Δt	absolute temperature difference between air and desiccant, °C

Greek symbols

ω	humidity ratio, g/kg
$\Delta\omega$	absolute ω difference between air and desiccant, g/kg
ϕ	relative humidity, %
ς	unmatched coefficient
η_{ex}	exergy efficiency of desiccant wheel

Subscripts

a	air
ch	chemical
d	desiccant
deh	dehumidification
dew	dew point
h	heat
in	inlet
m	mass
mix	mixture
out	outlet
p	processed air
r	regeneration air
reg	regeneration
t	temperature
th	thermal
tr	transfer
0	dead point

A desiccant wheel is actually a device for heat and mass transfer. Temperature and vapor pressure (or humidity ratio) differences (Δt and $\Delta\omega$, respectively) between the air and desiccant are the driving forces of heat and mass transfer during dehumidification and regeneration processes, and they lead to heat and mass transfer exergy destruction. The uniformity of Δt and $\Delta\omega$ fields has been shown to have tremendous influence on the heat and mass transfer ability in sensible heat exchangers and liquid desiccant dehumidifiers/regenerators [15–17]; the greater the uniformity, the stronger the heat and mass transfer ability. The concept of a uniformity factor and an unmatched coefficient (the square of the reciprocal value of the uniformity factor) has been introduced to describe the uniformity of Δt and $\Delta\omega$ fields during heat and mass transfer processes [15–17]. It will be extremely important to determine what, if any, connections exist between the uniformity of Δt and $\Delta\omega$ fields and exergy destruction.

This paper discusses various ways to lower the regeneration temperature from the perspective of exergy. The relationship of the uniformity of Δt and $\Delta\omega$ fields in the desiccant wheel to exergy destruction is examined; based on this connection, the influences of F_r and A_r on exergy destruction can be determined. The influences of both the number of dehumidification stages and pre-cooling are analyzed through their effects on the thermal exergy obtained by the processed air. Mathematical models of desiccant wheels are used as tools during performance analysis. The models' set up and validations by experimental results have been published in the previous research [8,18], which will not be talked about in this paper.

2. Exergy analysis of the desiccant wheel

The operating principle of a typical rotary wheel system is shown in Fig. 1. A desiccant wheel rotates between the regeneration air (*RA*) side and the processed air (*PA*) side to realize continuous dehumidification of the processed air. The processed air and the regeneration air flow in reverse in the direction of the wheel's thickness. Regeneration air has to be heated from state A_{rin} to state A_{r1} in order to supply enough heat for desiccant regeneration. Fig. 1(b) shows that during the dehumidification and regeneration processes in the desiccant wheel, both the processed air and the regeneration air change states near the isenthalpic lines. During dehumidification or regeneration, heat and mass are transferred in opposite directions, and the air is heated and dehumidified or cooled and humidified. The processed air after dehumidification has to be cooled down by extra cooling sources before being supplied into the indoor environment.

2.1. Exergy balance for the rotary wheel

Exergy of humid air per kilogram of dry air (ex) at atmospheric pressure can be described by Eqs. (1)–(3) [19], representing the theoretical maximum work that can be obtained when the air reaches the dead state (T_0, ω_0). The two terms on the right side of Eq. (1) are thermal exergy (ex_{th}) and chemical exergy (ex_{ch}), respectively.

$$ex(T_a,\omega_a) = ex_{th}(T_a) + ex_{ch}(\omega_a) \tag{1}$$

$$ex_{th}(T_a) = c_{pa}T_0\left(\frac{T_a}{T_0} - 1 - \ln\frac{T_a}{T_0}\right) \tag{2}$$

$$ex_{ch}(\omega_a) = R_aT_0\left[(1+1.608\omega_a)\ln\frac{1+1.608\omega_0}{1+1.608\omega_a} + 1.608\omega_a\ln\frac{\omega_a}{\omega_0}\right] \tag{3}$$

The exergy diagram of humid air is shown in Fig. 2, and the dead point (T_0, ω_0) is selected as the saturated state at ambient air temperature [11,20]. The influence of T_a on thermal exergy (ex_{th}) and